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Mach-6 Integrated Systems Tests of the NASA Lewis Research Center Hypersonic Tunnel Facility

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MACH-6 INTEGRATED SYSTEMS TESTS OF THE NASA LEWIS RESEARCH CENTER HYPERSONIC TUNNEL FACILITY

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ABSTRACT

This report documents the results for a series of 15 Integrated Systems Tests which were conducted at the NASA Lewis Research Center's Hypersonic Tunnel Facility (HTF) with test conditions simulating up to Mach-6 flight conditions. Facility stagnation conditions up to 3050 °R and 1050 psia were obtained with typical test times of 20 to 45 sec. The HTF is a free-jet, blowdown propulsion test facility that can simulate up to Mach-7 flight conditions with true air composition. Mach-5, -6, and -7 facility nozzles, each with a 42-in. exit diameter, are available. The facility, without modifications, can accommodate models approximately 10 ft long. Nitrogen is heated using a graphite core induction heater; ambient oxygen is added downstream to produce simulated air. The combination of clean-air, large-scale, and Mach-7 capabilities is unique to the HTF. Reactivation of the HTF was accomplished between 1990 and May 1994. This activity included refurbishing the graphite heater, the steam generation plant, the gaseous oxygen system, and all control systems. All systems were checked out and recertified, and environmental systems were upgraded to meet current standards. The data systems were also upgraded to current standards and a communication link with NASA-wide computers was added. In May 1994 a short-duration integrated systems test (approx. 2 sec) was conducted to verify facility operability. This test activity identified several modifications and corrections to the HTF which were required to improve overall facility performance. From the end of 1994 to April 1995 these items were completed, and the 3000-ft long, 30-in.-diam. steam supply line was insulated to improve system efficiency and allow operation in all weather conditions. Through May 1995 the test series which will be described in this report were conducted. During this activity, significant test experience was gained. The graphite storage heater was used at up to the maximum operating temperature of 5000 °R, several improvements were made to various facility systems and test procedures, and some operational problems experienced in the past were resolved (i.e., elimination of water backflow during shutdown). The HTF was operated with significant run times for the first time since being reactivated, and for the first time in more than 20 yr. Overall this test program resulted in smooth, relatively trouble-free facility operation and served to successfully demonstrate the operating capability and reliability of the HTF.

INTRODUCTION

The NASA Lewis Research Center Hypersonic Tunnel Facility (HTF), located at the Plum Brook Station, is a blowdown, nonvitiated free-jet facility capable of testing large-scale propulsion systems at Mach numbers up to 7. Hypersonic engines and models typically up to 10 ft in length and 2 ft in diameter can be tested. Major features and an operating map of the HTF are shown in figures 1 and 2. Illustrations of the major HTF components are presented in figures 3 and 4. The energy source is the graphite induction nitrogen heater, which can supply nitrogen up to 130 lb/sec at initial conditions of 5000 °R and 1200 psia. Nitrogen is supplied from a railcar. The hot nitrogen from the heater flows through graphite-lined, water-cooled piping, through an isolation valve, and into a water-cooled mixer. Oxygen and diluent nitrogen are added to the hot nitrogen through an injection flange upstream of the mixer to produce a test flow with true temperature, composition, and altitude simulation. The HTF facility is unique because it combines the capabilities of large scale (42-in. nozzle exit diam.) and Mach-7 enthalpy clean air.

Reactivation of the facility was initiated in 1990[1,2] and completed May 1994[3]. The reactivation work included rebuilding the graphite heater; dismantling and rebuilding the steam plant; changing the oxygen system design; and refurbishing the valves, pumps, and tanks of the oxygen, nitrogen, and water systems. High pressure systems were recertified, and the rehabilitation of electrical, instrumentation, and control systems was completed. All systems were checked out, serviced if needed, and made operational. All gas supply systems were checked for leaks, the valves were operated, and the control systems were verified. In May 1994, an abbreviated integrated systems test (IST) was performed. This was a short-duration test (approx. 2 sec) and included only the heater nitrogen flow (no diluent oxygen or nitrogen was added). This IST, however, verified that all facility systems operated successfully together as designed.

The reactivation activity, system checkouts, and the IST identified several modifications or corrections to the facility, and some changes to the operating sequences and procedures which were needed to improve overall facility performance and reliability. From May 1994 to April 1995 these modifications, repairs, upgrades, and procedural changes were implemented. The 3000-ft-long, 30-in.-diam. steam supply line was also insulated to improve system efficiency and allow operation in all weather conditions. The steam line required significant preheat time when exposed to rain or very cold temperature, making the operation of this system difficult and inefficient. Through May 1995 the Mach-6 Integrated Systems Testing, which is the subject of this report, was conducted.

MACH-6 INTEGRATED SYSTEMS TEST RESULTS

The HTF was operated for a series of 15 tests using the Mach-6 facility nozzle. Figure 5 shows the steam ejector in operation during an integrated systems test. Facility stagnation conditions up to 3050 °R and 1058 psia were obtained for test times of 20 to 45 sec. This test program was the first time that the HTF was operated with significant run times in more than 20 yr. Through the course of this activity facility systems or hardware problems were resolved and operating procedures were refined. The culmination of this test program resulted in smooth, relatively trouble-free facility operation and served to successfully demonstrate the operating capability of the HTF.

TEST MATRIX

Flow conditions and details of the test conducted during this IST series are outlined in table I. Testing progressed from lower temperature, nitrogen only runs, to high temperature runs using both oxygen and nitrogen diluent. A total of 15 successful tests were made out of 20 attempts (14 of the last 15 run attempts were successful). Several of the initial tests were unsuccessful because of various hardware problems within the facility systems. Throughout the test program, any operational problems identified were fixed prior to the next attempt. Resolving operational problems and fine-tuning the control valves within the facility gas systems were objectives of these checkout tests. The targeted operating condition was not reached for all tests, however, all successful runs resulted in several seconds of nitrogen flow through the heater (and diluent flows if called for) and provided valuable facility checkout data.

GRAPHITE HEATER CHECKOUT AND USAGE

During this test activity, the graphite heater was operated and checked out at near maximum temperature and pressure, and data were obtained to correlate the output temperature of the hot nitrogen as a function of the heater condition. Figure 6 is a cutaway view of the nitrogen heater, which consists of a stacked array of 15 cylindrically shaped graphite blocks, 6 ft in diameter and 2 ft in height, with 1100 holes drilled through each block to enhance heat transfer. A photograph of an individual block is presented in figure 7. Hexagonal graphite block keys assure the proper alignment of the drilled holes. Current is passed through the water-cooled copper induction coils; a 180-Hz, single-phase, 750-V supply (3 MW) is used to induce a magnetically coupled current in the outer diameter of the carbon graphite blocks. The graphite blocks are then heated as a result of their resistance to the induced current. Heating occurs slowly to reduce thermal stresses. Heating to the various sections of the graphite blocks is controlled independently yielding temperature gradients in the heater. The temperatures measured in different sections of the heater, as well as the average temperature, are presented in table I. During this test series, block temperatures of approximately 5000 °R, and heater average temperatures of over 4500 °R were reached. As experience in controlling the heater was gained, improved heater temperature uniformity was achieved. Further testing will enable continued refinement of heater controls and increasing heater temperature uniformity. The net temperature of the hot nitrogen exiting the heater may be lower than the average temperature of the heater blocks because of the required temperature gradients for heat transfer into the gas.

Figure 8 presents the results of calculations which predict the temperature of the hot nitrogen exiting the graphite heater as a function of time, assuming an initial uniform bed temperature of 4500 °R (which was near the maximum average temperature reached during the present study). The net temperature gradient between the heater blocks and the hot nitrogen increases with nitrogen flow rate (initially 300 °R at the maximum nitrogen flow rate of 130 lb/sec). As the graphite storage heater releases energy to the flow, the block temperatures drop; the exit nitrogen temperature also drops. For test conditions where diluent nitrogen is needed, the facility operating condition can be maintained constant as the hot nitrogen temperature decreases by changing the split between hot and diluent nitrogen (until the maximum hot nitrogen flow rate is reached). For Mach-7 simulation only, hot nitrogen and diluent oxygen are used; therefore, the net facility stagnation temperature will decrease with time. For high temperature and pressure operation, the test duration may be limited by the temperature drop in the hot nitrogen and the ability of the facility to maintain the required conditions. The facility total temperature probe was operational during only the last four tests; however, this provides an accurate measurement of facility total temperature. Facility total temperatures predicted assuming a hot nitrogen supply temperature equal to the average block temperature (and ambient diluent flows) are shown in table I. These predicted facility total temperatures for the tests accomplished in this series are 100 to 300 °R higher than the measured total temperature. This difference depends on the hot nitrogen flow rate, the heater temperature and temperature gradient, and overall thermal losses; however, these results are consistent with predictions.

FACILITY OPERATION, FLOW CONTROLS, AND TEST CAPABILITY

A schematic of the facility components and gas supply system is shown in figure 9. A significant focus of this test program was to tune the control systems and valves, and gain operating experience. This included tuning the main nitrogen control valve for the heater bed ramp (V4301), the diluent cold nitrogen supply (V435), and the diluent cold oxygen (V100). A block diagram of the HTF control system is shown in figure 10. The control system consists of four major components: a Test Matrix Sequencer (TMS), a Programmable Logic Controller (PLC), an analog flow computer, and the hydraulic valve controllers. A typical facility run is completely automated by means of this control system. The overall control system is responsible for setting up the facility support systems prior to bed ramp, initiating the bed ramp and setting the tunnel conditions, and then shutting down the facility support systems after the run is complete. Valve controllers are used to operate the facility control valves which set the facility operating conditions. Valve V4301 sets the facility run pressure, valve V435 sets the amount of cold nitrogen flow, valve V100 sets the amount of oxygen, and valve V4326 is used to vent the facility during shutdown. The TMS, which is a PC-based system that is responsible for issuing the supervisory commands that execute the entire tunnel run, is fully programmable and allows for the programming and selection of desired run conditions. It generates the analog setpoints to the valve controllers that set the tunnel conditions. It also generates the startup and shutdown commands to the PLC, which in turn controls the facility support systems. The flow computer calculates the actual cold nitrogen and oxygen flow rates from orifice instrumentation and converts them into feedback signals that are used by the cold nitrogen and oxygen controllers. The flow computer also provides limited error checking on facility parameters to ensure proper operation. In general, the control system allows for automatic operation of the facility during a run. The functionality of the system components was checked out prior to the IST runs. During the IST runs, the system functioned properly; only valve controller tuning was required.

During this test series, the necessary procedures and techniques were developed to allow smooth, accurate, and consistent facility start (ramp) up, on condition operation, and shut (decay) down. Particularly during the last four integrated systems tests, the operation of the HTF was as planned; the ramp up and down were accomplished smoothly, and the operating conditions desired were reached and held sufficiently constant for the specified run time. Figures 11 and 12 show time histories of facility test flow conditions, including total mass flow rate, stagnation pressure, total temperature, and test cabin pressure (vacuum), for two integrated system tests (IST 12 and 13). These tests were at simulated Mach-6 conditions and high pressure, and the total temperature probe was operational. For both of these tests the ramp-up and -down times were 45 to 50 sec. Depending on the test conditions during this test program the ramp-up and -down times ranged from 25 to 50 sec in order to minimize the loading on the heater blocks. The time on condition was held between 10 and 45 sec. Choosing this time was based on the time required to tune the facility systems and valves. The maximum possible operating-time on condition is in general limited by one of the following: the heat capacity of the graphite blocks coupled with the maximum allowable gas temperature drop, the maximum capacity (4.9 min of operating time) of the steam accumulators and ejector system, or the thermal limitations of facility components or test hardware. Table II outlines predicted operating ranges and maximum run times with each of the three nozzles installed. This summarizes specific test points on the operating envelope (fig. 2) which spans from 68 000- to 120 000-ft altitude, 70- to 1200-psia nozzle inlet stagnation pressure, and 2200 to 4200 °R nozzle inlet stagnation temperature.

The HTF was operated up to a condition of 3050 °R and 1050 psia during the present study. This test condition corresponded to Mach-6 flight simulation. The maximum temperature obtained was limited by the Chromel-Alumel thermocouple probes used in the facility mixer section. When Mach-7 conditions are desired, these probes will be replaced with a high temperature design. The heater conditions achieved, however, verified the ability of the HTF to reach the operating range shown in figure 2.

RESOLUTIONS OF PAST OPERATIONAL PROBLEMS

A previous issue of significant concern was an erosion problem with the carbon felt in the heater, the graphite lining in some of the hot train components, and to a lesser extent, the graphite heater blocks. During testing in the 1970's[4], this erosion problem resulted in both a decreased temperature capability for the facility and significant visible carbon particulate levels. This problem caused some concerns relative to the HTF's operational capability. The first issue was whether carbon particulates were a source of test flow contamination that could affect test results, particularly in a combustion experiment. Another issue was erosion of the surface or leading edge of experimental hardware (i.e., engine model). The erosion was attributed to water in the heater from leaks in the water cooling coils or more significantly, "flashback" from spray cooling in the exhaust ejector. During reactivation, various upgrades were made to the facility to eliminate any potential leaks of coil cooling water into the heater. The operating procedures and sequences were modified to prevent water backflow into the facility. This sequence now involves taking the spray cooler off-line while there is still flow in the test section and opening a test cabin vent. This establishes an air flow into the cabin and through the diffuser and serves to blow out any standing water in the diffuser before the ejector is shut off. This should prevent any water backflow into the facility, eliminating any water from entering and accumulating in the graphite heater. Therefore, any significant erosion of the graphite components will be prevented.

During the first two tests of this series, some water backflow into the test cabin occurred. However, no water entered the heater or hot train components. The facility shutdown procedures were refined during these tests, and during the last 13 tests of this series, no water backflow was observed. Resolving this erosion problem was a major accomplishment. It is expected that some minimal erosion of the graphite components will occur during normal operation. Gas sample surveys will be made during future testing to monitor levels of CO_2. High levels of CO_2 would indicate an imminent erosion problem.

UNIQUE VALUE AND APPLICATIONS OF HTF CAPABILITY

The HTF is unique because of a combination of large scale and clean air. Results obtained in vitiated facilities are expected to require correction; however, the magnitude of this correction is unknown because of limited data. Tests in the HTF could resolve this critical issue. Design work has been completed for a system that will permit contaminants to be added to the HTF test flow, allowing tests with both clean and vitiated air. Thus a direct examination of these contaminant effects on performance will be possible.

During scramjet engine flight tests, the number of measurements and test conditions are limited. Ground test data can provide more detailed information which is required to interpret the flight test results and allow refinement of the propulsion system. This process is complicated by any correction required for free-stream contamination. Data from a clean-air facility such as the HTF will not require any such correction, resulting in a more accurate assessment of the propulsion process. The HTF provides a critical capability for the research and development of ramjet/scramjet propulsion systems.

Facility nozzles for Mach numbers lower than 5 could be fabricated and additional dilution air added to lower the test flow temperature to match the required flight conditions. The facility could also be modified to add a vitiated heater downstream of the mixer to provide near a Mach-10, direct-connect combustion test capability.

CONCLUDING REMARKS

The NASA Lewis Hypersonic Tunnel Facility (HTF) is a unique national asset because of the combination of large scale and clean air. The facility had been used in the past for Mach-5, -6, and -7 engine testing and became available again for hypersonic propulsion testing after completion of an extensive reactivation from 1990 to 1994. During the integrated systems tests, the facility operating capability was demonstrated, and significant test experience was gained. The HTF heater was operated at near maximum temperature, and operational problems experienced in the past were resolved. The facility ran smoothly and relatively trouble free and is now fully operational. Further work is needed and planned on the facility fuel system, model injection system, and propulsion test specific systems and requirements. The major effort, however, has been completed. The capability has been demonstrated. The NASA Lewis Hypersonic Tunnel Facility is available to support the development of hypersonic propulsion systems for the 21st century.

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3. Thomas, Scott R.; Trefny, Charles J.; and Pack, William D.: Operating Capability and Current Status of the Reactivated NASA Lewis Research Center Hypersonic Tunnel Facility. AIAA-95-6146, April 1995 (NASA TM-106808).

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TABLE I.—INTEGRATED SYSTEMS TESTS DATA

Test number	Data number	Predicted total temperature, °R	Measured total temperature °R	Measured total pressure, psia	Mass flow lb/sec	Time on condition, sec	Ramp-up time, sec	Ramp-down time, sec	Average bed temperature, °R	Bed temperature distribution, °R				
										1	2	3	4	5
1	1076	2903	----	472	90	0	0	0	2903	2975	3033	3266	2759	2484
2	No data taken	----	----	----	----	0	----	---	---	---	----	----	----	----
3	1261	2514	----	472	90	20	35	40	2514	2690	----	2967	2402	1995
4	1454	2217	----	472	88	30	25	40	2822	3281	----	3449	2452	2105
5	1455	2225	----	472	91	0	20	35	2834	3322	----	3447	2525	2041
6	1664	2220	----	472	91	30	30	30	2827	3329	----	3415	2480	2085
7	1667	2242	----	472	91	0	15	30	2856	3330	----	3461	2571	2060
8	1668	2166	----	472	91	10	25	40	2754	3204	----	3335	2449	2026
9	2277	3300	----	1058	170	0	40	45	4420	4978	4477	4530	4389	3726
10	2278	3380	----	900	141	30	35	40	4548	4952	4636	4745	4508	3900
11	2441	3321	----	900	145	0	7	20	4035	4338	----	4189	4072	3539
12	2442	3300	3050	900	145	20	50	45	4009	4289	----	4132	4060	3555
13	2635	3208	3000	1050	178	30	50	45	3709	3829	----	3891	3794	3320
14	2636	2827	2740	900	162	20	40	40	3334	3537	----	3546	3305	2946
15	2638	2412	2300	850	172	45	40	50	2862	3092	----	3093	2810	2454

TABLE II.—UPPER AND LOWER LIMITS OF HYPERSONIC TUNNEL FACILITY (HTF) TEST FLOW CONDITIONS

Mach number	Nozzle					Test section			
	Pressure, psia	Temperature, °R	Flow, lb/sec	Throat diameter, in.	Exit diameter, in.	Static pressure, psia	Static temperature, °R	Altitude, ft	Run times, sec
5	410 70.5	2200 2420	189 30.9	7.2 7.2	42	0.74 .118	384 428	68×10^3 108	[a]103 [b]294
6	1200 144	2965 3310	222 25.4	4.9 4.9	42	0.61 .071	390 451	72×10^3 120	[a]42 [b]294
7	1200 430	3830 4190	104 36.19	3.5 3.5	42	0.33 .071	412 451	93×10^3 120	[a]90 [c]180

[a]Limited by maximum gas temperature change of 200 °F.
[b]Limited by steam availability at 150 psig.
[c]Limited by diffuser temperature limits.

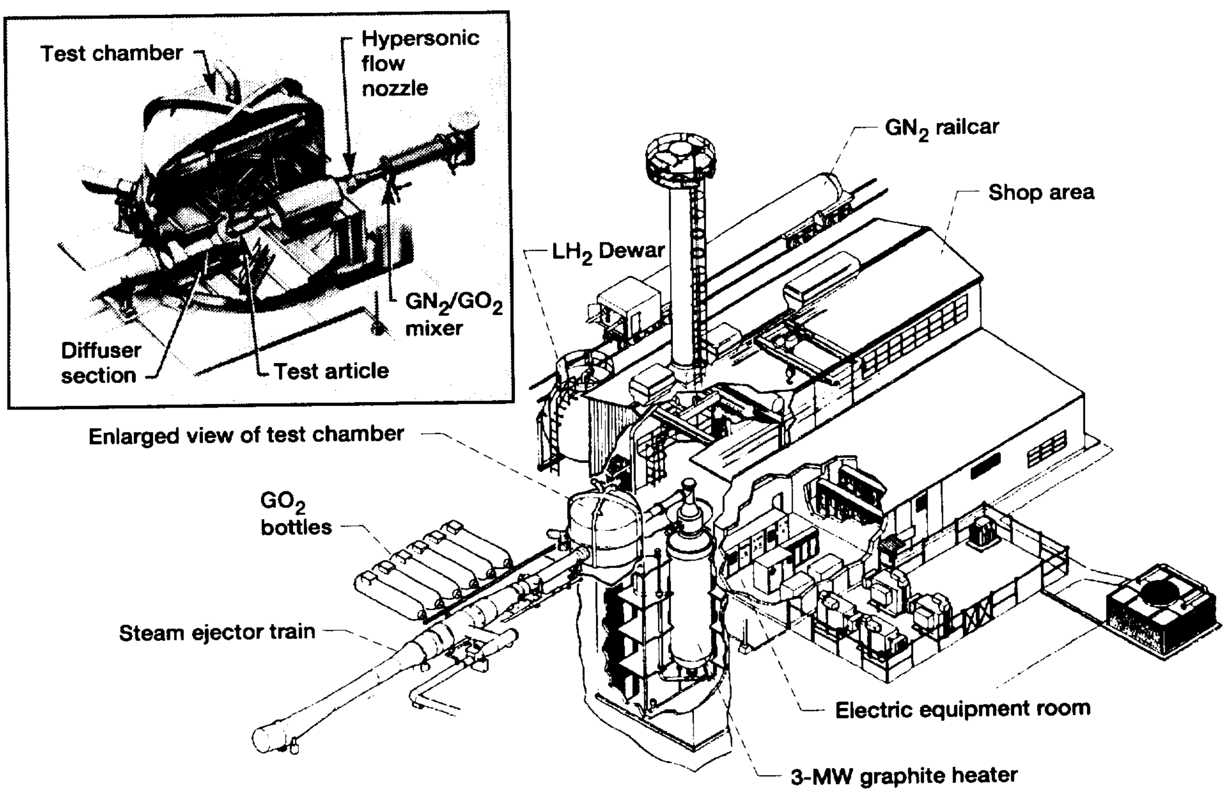

Figure 1.—Cutaway view of hypersonic tunnel facility (HTF).

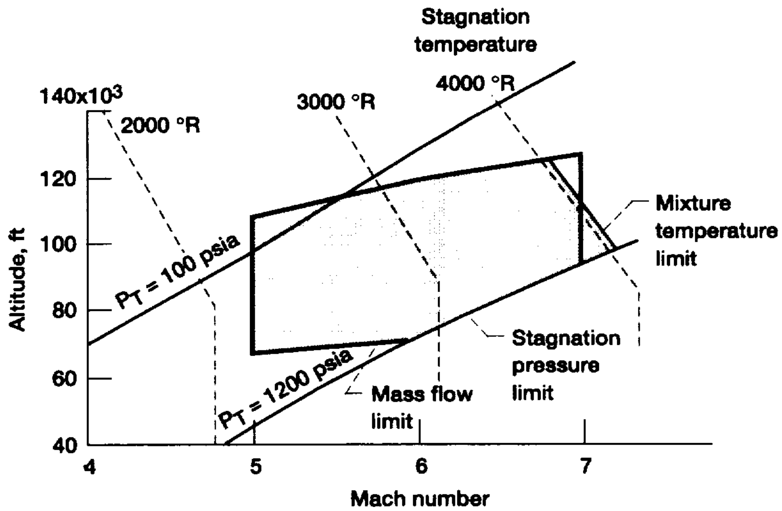

Figure 2.—Hypersonic tunnel facility (HTF) operating envelope.

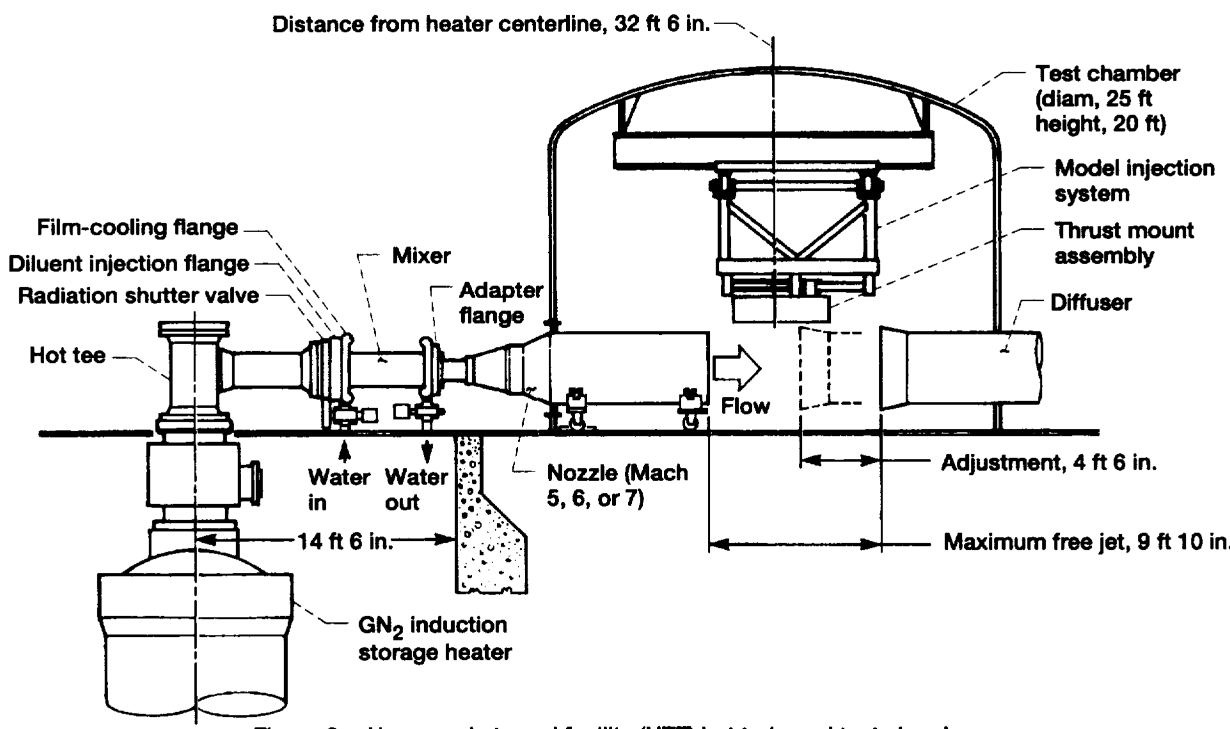

Figure 3.—Hypersonic tunnel facility (HTF) hot train and test chamber.

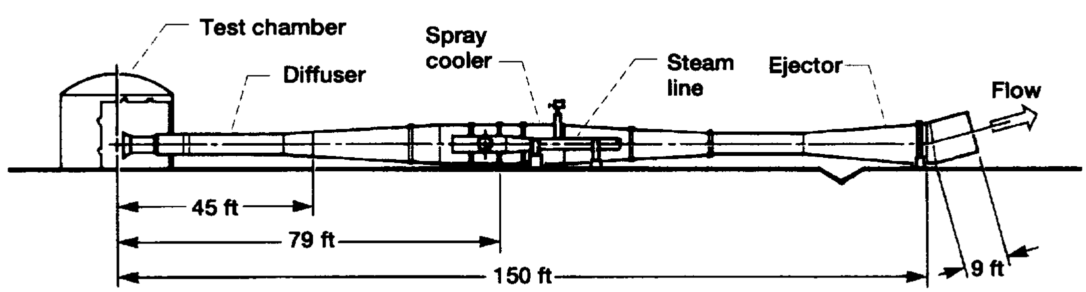

Figure 4.—Hypersonic tunnel facility (HTF) diffuser and ejector.

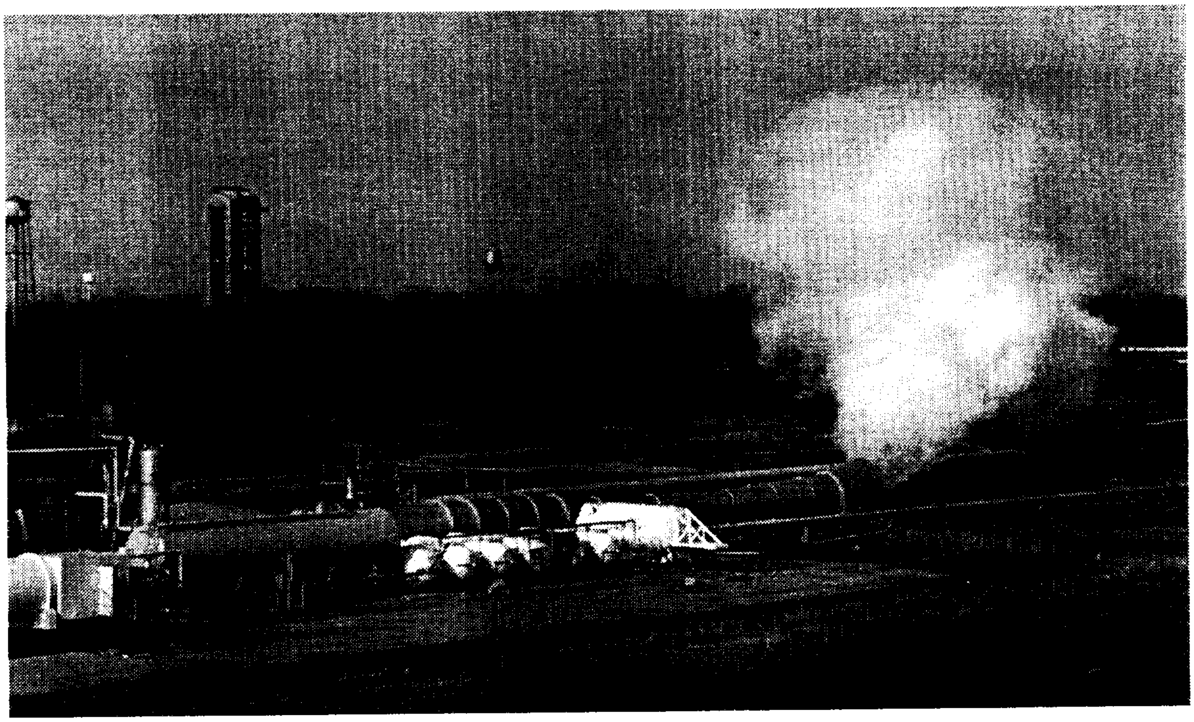

Figure 5.—Hypersonic tunnel facility (HTF) steam ejector in operation during integrated systems test (IST).

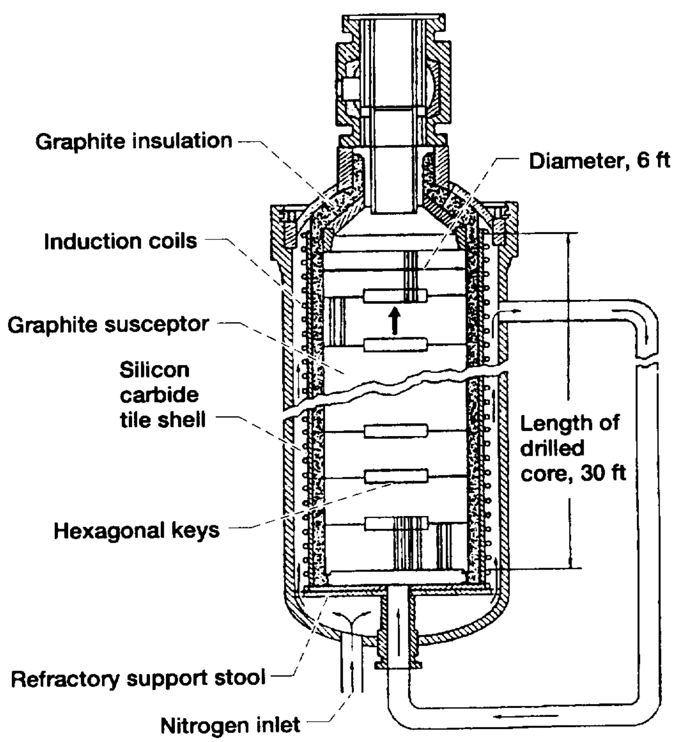

Figure 6.—Nitrogen induction storage heater.

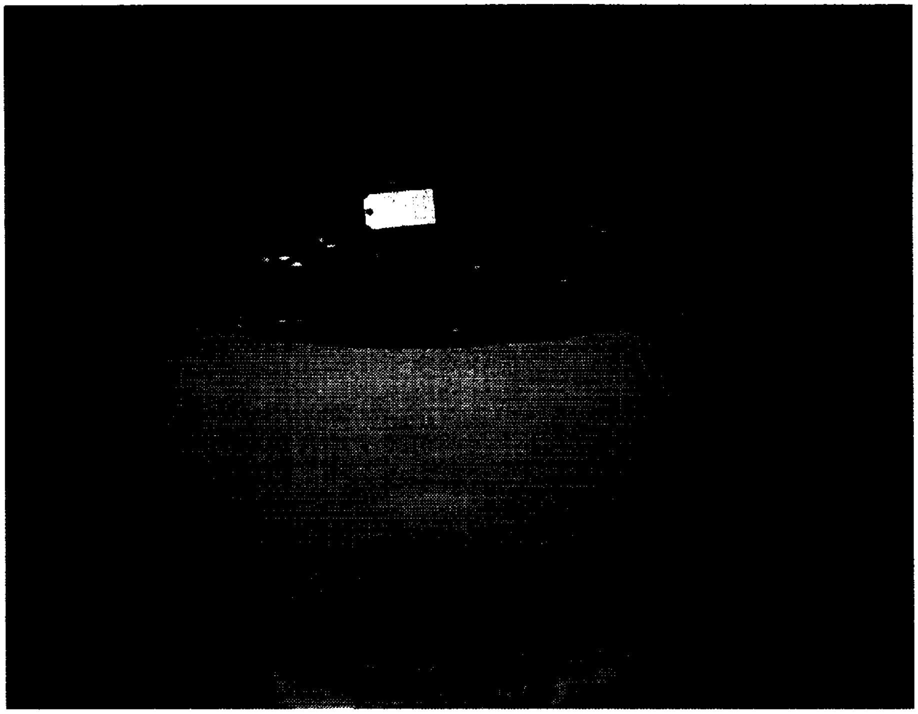

Figure 7.—Graphite block from induction storage heater.

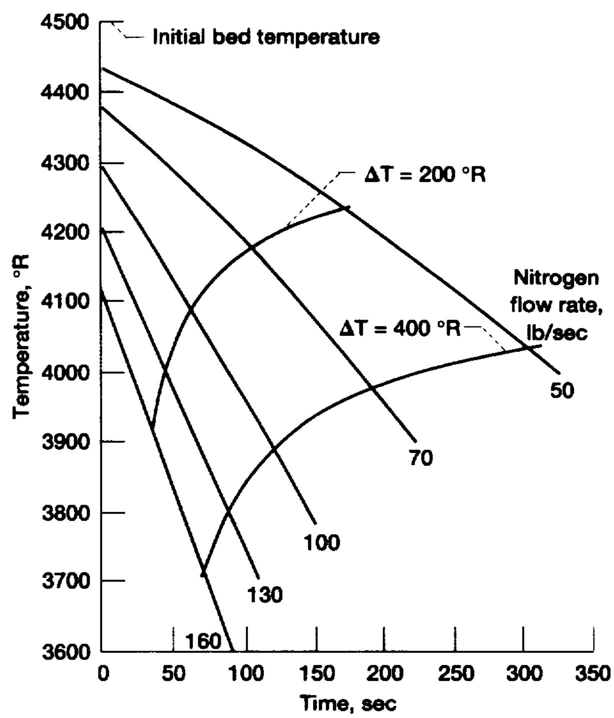

Figure 8.—Nitrogen temperature exiting graphite heater. Exit nitrogen temperature versus running time; 4500 °R initial bed temperature.

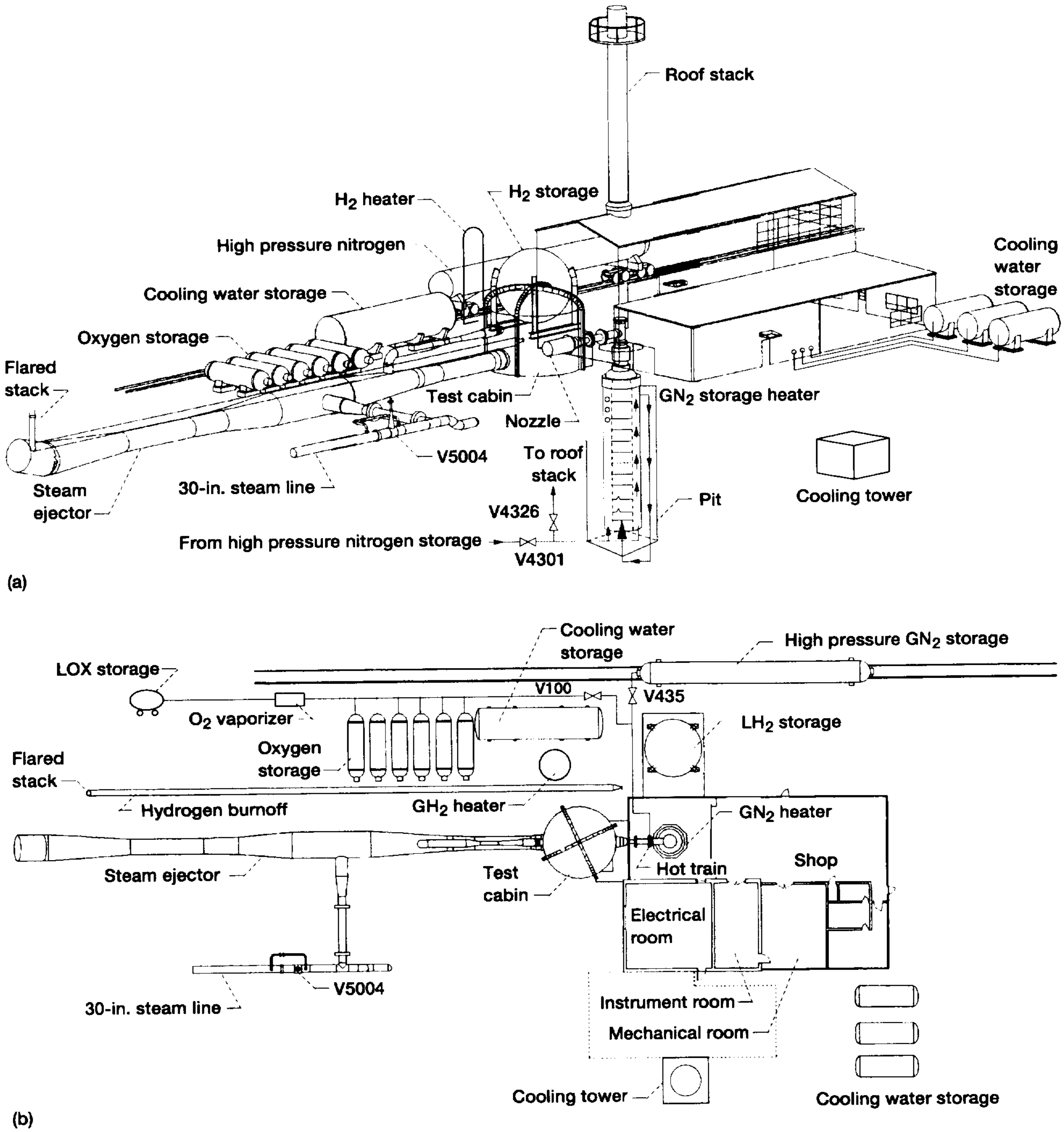

Figure 9.—Schematic of facility components and gas supply system. (a) Elevated view. (b) Plan view.

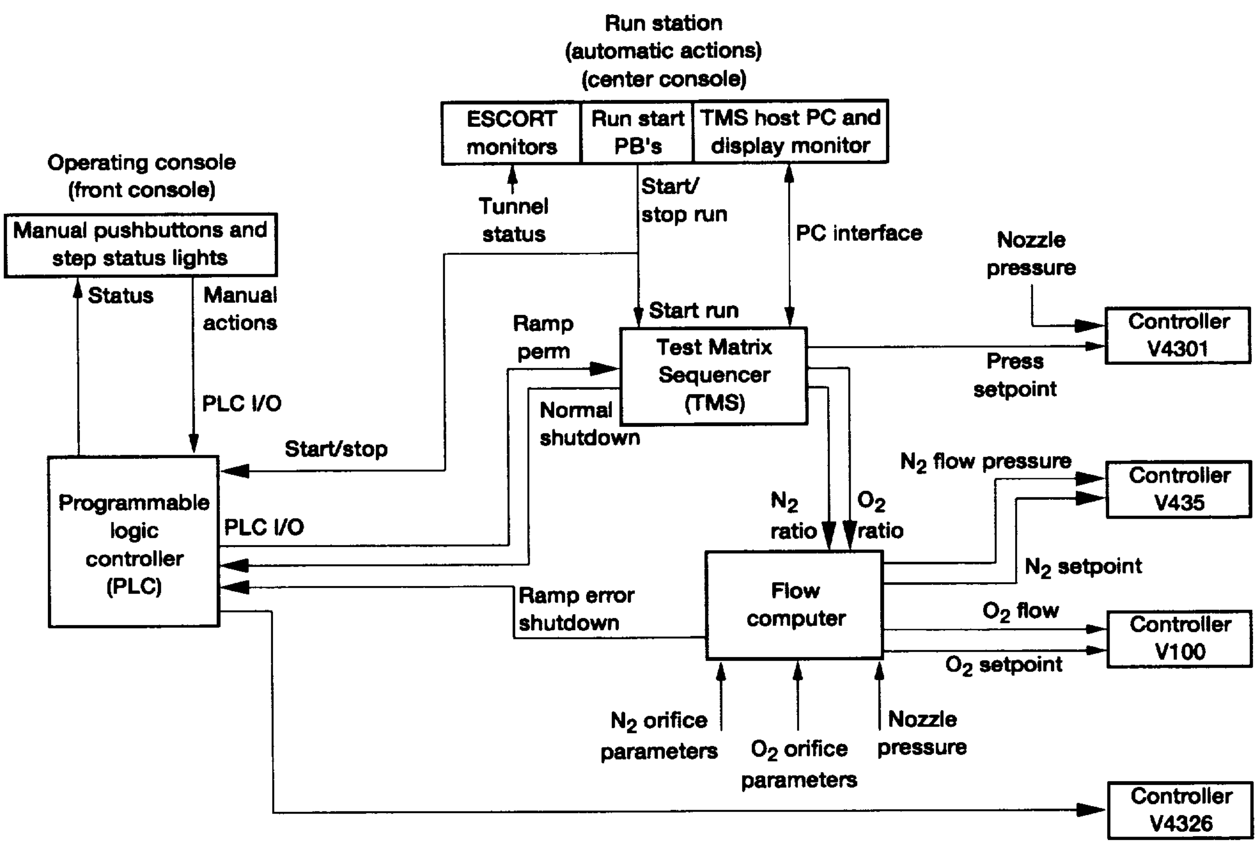

Figure 10.—Block diagram of hypersonic tunnel facility (HTF) control system.

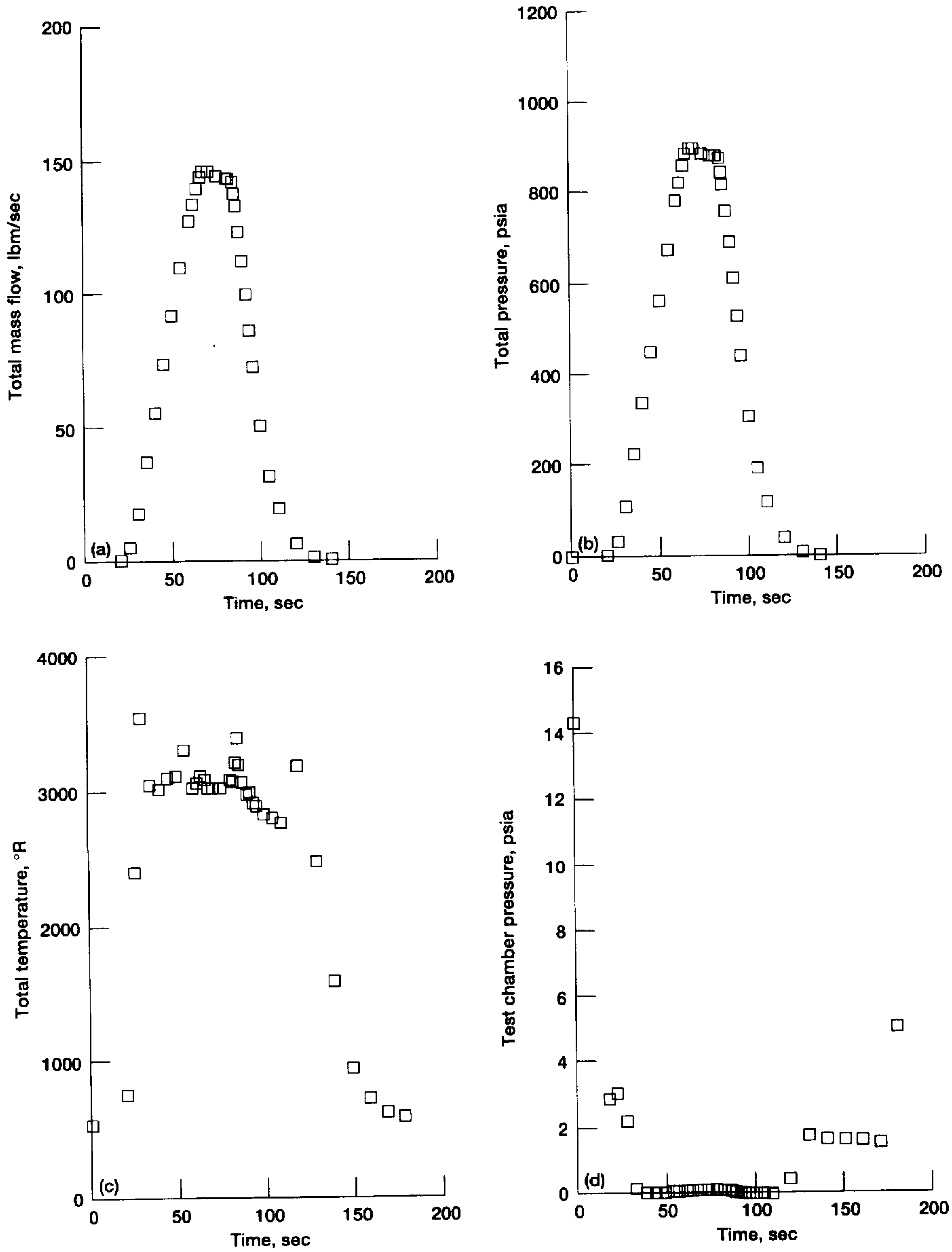

Figure 11.—Time histories of flow properties for IST 12. (a) Total mass flow rate. (b) Facility (mixer) total pressure. (c) Measured total temperature. (d) Test cabin pressure.

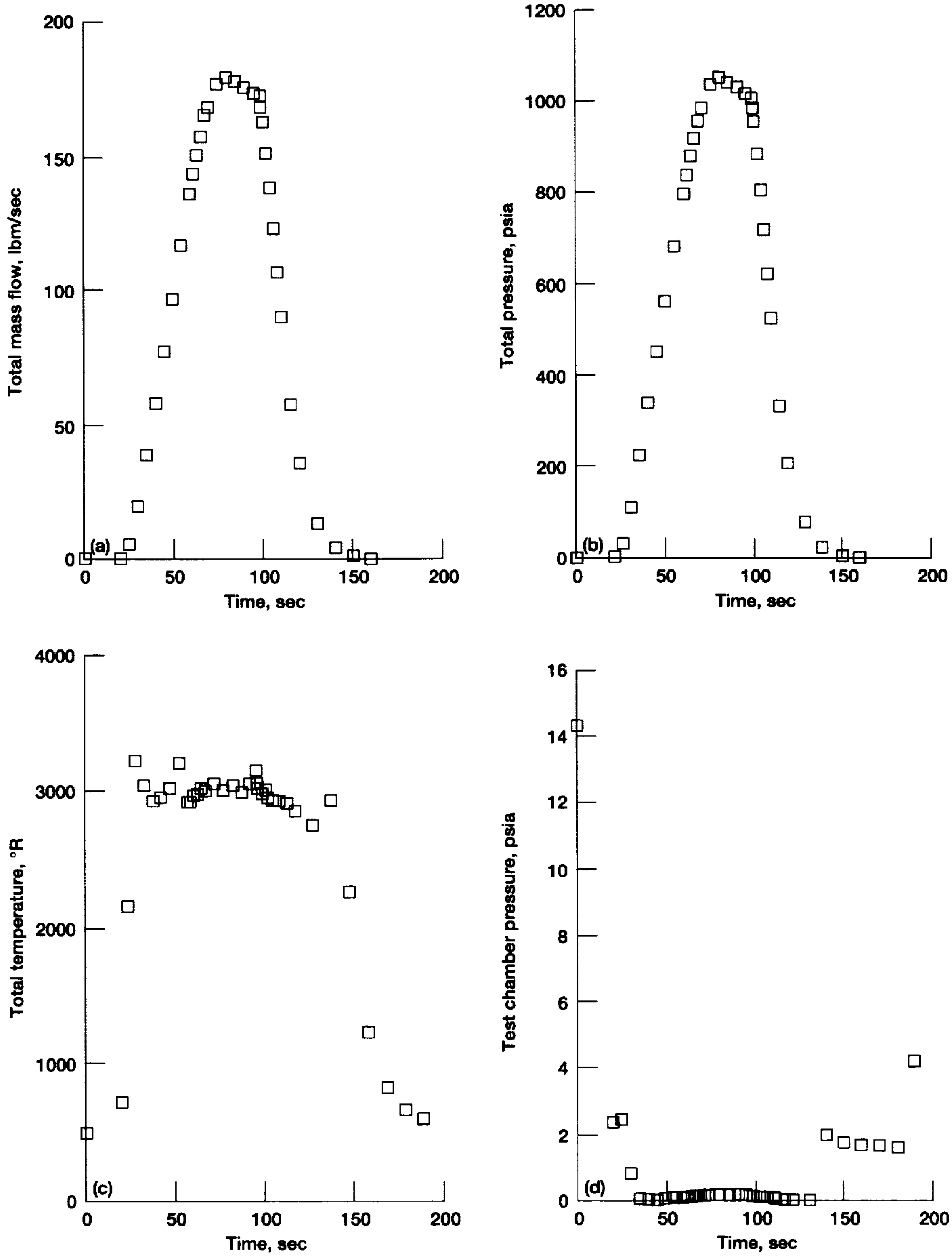

Figure 12.—Time histories of flow properties for IST 13. (a) Total mass flow rate. (b) Facility (mixer) total pressure. (c) Measured total temperature. (d) Test cabin pressure.

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13. ABSTRACT ***(Maximum 200 words)***

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